COMPARISON OF ATMOSPHERIC ENVIRONMENTAL INTRUSIONS OF VARIOUS POWER PLANTS

Wm. H. Fischer
Gilbert/Commonwealth
Reading, PA 19603

INTRODUCTION

The conversion of coal into useful products by combustion or gasification results in the emission of waste materials that are undesirable additions to the environment. These emissions must be controlled in order to prevent damage to the environment, its inhabitants, and their possessions, and to comply with regulations. The objective of this environmental analysis is to assess and compare the environmental intrusions into the atmosphere of conventional coal-fired electric utility plants burning pulverized coal (PC), pressurized fluidized bed combustion power plants (PFBC), coal gasification combined cycle power plants (CGCC), magnetohydrodynamic power plants (MHD), and molten carbonate fuel cell power plants (MCFC). The plants are ranked according to their rates and amounts of emissions.

EMISSIONS

The combustion of coal or of coal-derived fuel gases results in the production and emission into the atmosphere of particulates, sulfur oxides (SO_x) nitrogen oxides (NO_x) and carbon oxides (CO_x). These are derived from the mineral matter in the coal, mineral and organic sulfur in the coal, and organic nitrogen in the coal, producting fuel NO_x. Additionally, the high combustion temperatures result in thermal NO_x being formed from nitrogen in the combustion air.

The particulate matter emitted when coal is converted consists primarily of ash derived from the mineral matter of the coal, mixed with some unburned coal, plus elutriated bed material, if any. In the event that the temperature of the flue gas drops below about 300°F, depending on sulfur content of the fuel, droplets of sulfuric acid may condense, giving rise to an acid aerosol or mist.

Coal sulfur is converted to oxides, SO_x, during combustion, or to H_2S during gasification. From combustion, over 95% is in the form of SO_2 , with less than 5% as SO_3, as emitted. Although SO_2 is considered harmful to health and welfare, SO_3 is even more so. After emission, the SO_2 is slowly converted to SO_3. The SO_3 combines with water vapor to form sulfuric acid mist or rain and with basic compounds to form sulfates. Emitted H_2S will also be oxidized to SO_3. Gasification also results in the formation of small amounts of COS and even smaller amounts of CS_2.

The nitrogen oxides NO and NO_2 are collectively called NO_x. NO_x is formed from nitrogen both in the fuel and in the combustion air. The percentage of fuel N_2 converted to NO_x

decreases as the percentage of fuel-bound nitrogen increases but the absolute amount converted increases, since the percentage conversion decreases less rapidly than the percentage contained increases. Sunlight converts the emitted NO_x, which is about 90 to 95% NO, into NO_2, which is unhealthful and contributes to acid rain by forming nitric acid. In addition to the NO_x from fuel discussed above, NO_x is also produced from the nitrogen in the combustion air. This is called thermal NO_x. The amount of thermal NO_x produced is a function of combustion temperature, combustion air ratio and dwell time.

The nitrogen-containing emissions from gasifiers arise only from the fuel nitrogen, since no thermal NO_x arises under the reducing conditions prevailing. The nitrogen-containing emissions are not NO_x but rather, ammonia, NH_3, and a trace of hydrogen cyanide, HCN. When the raw fuel gas is burned, the nitrogen compounds will convert nearly quantitatively to NO_x and thermal NO_x will also be formed. This can easily result in excessive final NO_x emissions. If the raw fuel gas is cleaned of ammonia, then final NO_x emissions will be reduced but not eliminated, since thermal NO_x will still be formed.

As an indication of the amounts of these emissions, a typical uncontrolled 1000 MW boiler burning coal containing 3.5% sulfur and 12% ash will emit around 900 tpd of ash, 600 tpd of SO_x, 100 tpd of NO_x, and 28,000 tpd of CO_2.

POWER PLANT EMISSIONS

The power plants considered in this task are so different in detail that any discussion must either be very general and thus superficial or very detailed and thus bewildering. An attempt will be made to steer between these obstacles. In general, an effort will be made to pick up the raw gases downstream of the primary energy converter in each power plant and to briefly describe how the gases will be brought into compliance with the emission limits given below.

The various power plants were nominally designed for 500 MWe output. Illinois No. 6 coal was used, of 3.5% sulfur and 12% ash, with a higher heating value of 11,500 Btu/lb. However, each design used a particular coal analysis which varied somewhat from these figures. The various outputs and efficiences are shown in Table 1, where columns 3 and 4 show the usual net figures. Pollutant emissions, though, come from the gross input, so gross figures are also shown in columns 2 and 5.

The pollutants in the raw gases emerging from the coal convertors in the various power plants are summarized in Table 2. These data have been collected and derived from various sources[1-6] as well as internal studies and computer simulations. They thus are indicative rather than representative and should be used for comparison only, not for design purposes. As the raw gases proceed through other portions of the power plants, their compositions can be expected to change. In general, the changes

TABLE 1

COAL CONVERSION PLANTS

Plant	MWe Gross	MWe Net	Efficiency (%) Net	Efficiency (%) Gross
PC	546	503	34.96	38.04
PFBC	513	497	39.75	41.01
CGCC	531	502	37.34	39.53
MCFC	533	460	49.94	57.74
MHD	624	504	40.49	51.79

TABLE 2

EMISSION RATES FROM COAL CONVERTORS
($lb/10^6$ Btu)

Plant	Particulate		SO_x		NO_x		CO_2
	U[A]	C	U	C	U	C	U
PC	8.6	0.03	4.9	0.6	0.6	0.6	203
PFBC	14.7	0.03	0.6	0.6	0.3	0.2	206
CGCC	5.1	0.03	4.9[B]	0.6	~0[C]	0.2[D]	203
MCFC	1.5	~0	4.9[B]	~0	0.6[C]	~0	203
MHD	20.2	0.03	~0	~0	0.6	0.6	214
Emission Limit	0.03		0.6		0.6		

A U = UNCONTROLLED, C = CONTROLLED

B SO_x EQUIVALENT IF ALL H_2S AND COS ARE CONVERTED TO SO_x

C NO_x EQUIVALENT IF ALL NH_3 IS CONVERTED TO NO_x

D THERMAL NO_x

are minor in heat removal or recovery sections but are major in gas cleanup sections. Combustion of fuel gases will increase the NO_x content due to thermal fixation of nitrogen in the combustion air.

Also shown in Table 2 are the emissions to the atmosphere after control measures have been applied to the raw gases. In general, the controls have been designed to comply with the EPA New Source Performance Standard (NSPS) for elecrtric utility steam generating units. Strictly speaking, this NSPS applies only to the pulverized coal (PC) and pressurized fluidized bed (PFBC) plants, but has also been used for the other plants in the absence of regulations for them. The exception is the molten carbonate fuel cell plant in which the requirements are set by the fuel cell. There is currently no emission limit for CO_2 from any plant, so no CO_2 control equipment is required.

PULVERIZED COAL POWER PLANT

A conventional pulverized coal-burning boiler raising steam for a turbine to generate electricity is considered, as shown in Figure 1. Figure 2 is a block diagram of the air pollution control equipment selected for this plant.

Particulates

The uncontrolled fly ash emission of 8.6 $lb/10^6$ Btu will be reduced to the compliance limit of 0.03 $lb/10^6$ Btu by a combination of an electrostatic precipitaor (ESP) and a wet scrubber. The ESP has a specific collection area (SCA) of 200 sq. ft. per 10^3 acfm. Its pressure drop is negligible.

Sulfur Oxides

The main task of the scrubber is not particulate removal but rather sulfur oxides removal. The theoretical SO_x emission is 5.2 $lb/10^6$ Btu but since five percent is assumed to be retained by the ash, 4.9 $lb/10^6$ Btu emerges. This must be reduced to 0.6 by means of a limestone flue gas desulfurization system employing a spray tower a at liquid-to-gas ratio (L/G) of 200 gpm per 10^3 acfm at a ΔP of 0.5 psi.

Nitrogen Oxides

A typical PC furnace will just about meet the NO_x emission limit. Use of retrofit low-NO_x burners in an existing installation or use of two stage combustion or low-NO_x burners in a new installation will insure compliance.

PRESSURIZED FLUIDIZED BED COMBUSTION POWER PLANT

A pressurized fluidized bed combustion power plant (Figure 3) has a steam cooled PFBC raising steam for electricity generation and providing hot gas for driving a gas turbine which compresses the

PFBC air and also generates electricity. A block diagram of the air pollution control equipment is shown in Figure 4.

Particulates

The particulate load from a PFBC is high due to carry over of ash in the feed coal, plus unburned coal, plus elutriated bed material. A series of high efficiency, high temperature cyclones reduces the loading to a low enough level to protect the gas turbine. However, this level, approximately 0.4 lb/10^6 Btu is still above the emission limit, so that a bag house is used to clean the cooled gas to compliance level. The total ΔP is 7 psi. Advanced design cyclones may be able to meet the emission limit, eliminating the bag house, but probably at an increased pressure drop.

Sulfur Oxides

The dolomite fed to the PFBC at a Ca/S mole ratio of 2.3 is calcined to the oxides. The calcium oxide reacts with the sulfur dioxide formed from the sulfur in the coal to produce calcium sulfate. The magnesium oxide does not react but improves the porosity and hence the reactivity and utilization of the calcine. Thus, the raw gas has a low enough SO_x content to be in compliance, but at the cost of having an increased particulate loading.

Nitrogen Oxides

The low combustion temperature in a PFBC retards the formation of thermal NO_x. Pressurized operation results in lower NO_x formation than does atmospheric operation. There is evidence that any NO_x formed is partially decomposed by reactions with sulfur dioxide and/or calcium sulfate. The net result is that NO_x emissions from a PFBC are below the emission limit, so that no additional control method is needed.

GASIFICATION COMBINED CYCLE POWER PLANTS

Another different system is shown in Figure 5, with the air pollution control equipment shown in Figure 6. Here, an air blown coal gasifier supplies the fuel gas for a gas turbine whose exhaust raises steam.

Particulates

A venturi scrubber at an L/G of 20 and a ΔP of 15 psi is used to remove the bulk of the particles from the fuel gas. Final removal occurs in the Stretford plant.

Sulfur Oxides

The sulfur in the coal appears principally as hydrogen sulfide in the fuel gas. This is removed as elemental sulfur by the Stretford unit for disposal or sale. Residual sulfur content, nearly all as carbonyl sulfide, is converted to sulfur dioxide in the gas turbine combustor but its emission is low enough to be in compliance with the regulations.

Nitrogen Oxides

The low pressure Combustion Engineering gasifier selected produces no ammonia from the coal nitrogen, so that the only NO_x released is that formed thermally in the gas turbine combustor. Conventional gas turbine control methods will assure compliance.

FUEL CELL POWER PLANT

This power plant, shown in Figures 7 and 8, is the most complicated one considered. It has three sources of electricity: fuel cells, a gas turbine, and steam turbines. The sensible heat in the gasifier fuel gas is used to raise steam, as is that in the gas turbine exhaust gas and the fuel cell effluent gas. The fuel cell effluent gas also drives the gas turbine. Finally, the chemical energy in the fuel gas drives the fuel cells.

Fuel cell gas cleanliness requirements are set by the fuel cells, not by emission standards, particularly for sulfur compounds, which must be reduced to 1 ppm. Particulate and ammonia are much less troublesome.

Particulates

A venturi scrubber with an L/G of 40 and a ΔP of 15 psi is used to remove particulate matter to a level sufficient to meet fuel cell requirements and thus emission standards.

Sulfur Oxides

The Texaco gasifier selected emits principally hydrogen sulfide, which is easily removed to the desired ppm level, but the carbonyl sulfide is not. Therefore, a hydrolyzer unit is used to convert the carbonyl sulfide to hydrogen sulfide. A Selexol unit is used to separate the hydrogen sulfide from the fuel gas. Claus-Beavon units are used to recover elemental sulfur and prevent sulfur emissions to the atmosphere in violation of applicable regulations. Final hydrogen sulfide removal is accomplished with a throw away bed of zinc oxide which adds another ΔP of 10 psi for a total ΔP of 25 psi.

It is obvious that the resulting low sulfur level in the fuel gas, after conversion to sulfur dioxide in the catalytic burner, is far below the permissible emission limit.

Nitrogen Oxides

The venturi particulate scrubber will remove most of the ammonia in the fuel gas so that little fuel NO_x will be formed. The temperature in the catalytic burner is low, about 1200°F, so that little if any thermal NO_x is formed[8]. The result is that final NO_x emissions are well in compliance.

MAGNETOHYDRODYNAMIC POWER PLANT

This power plant, shown in Figures 9 and 10 is completely different from those discussed heretofore. Coal is burned in a three stage combustor. The first stage operates with about 50% of stoichiometric oxygen and rejects molten slag. The second stage operates at about 95% of stoichiometry with additional slag rejection and is followed by a third stage where seed material (a mixture of potassium sulfate and carbonate) is added. After generating direct current electricity in a channel, the plasma is finally combusted at about 105% stoichiometry with added air with additional slag and seed rejection. Steam is raised by the hot gas to generate alternating current electricity. Particulate matter is removed for recovery of the seed material and the gas is discharged to the atmosphere.

Particulates

Despite the rejection of slag, the addition of seed material results in a very high particulate loading in the raw gas. An ESP with an SCA of 500 is used to remove the solids down to the compliance limit. An unusually large SCA is required because of the high electrical resistivity of the seed compounds.

Sulfur Oxides

The seed material serves a dual purpose. The potassium contributes conductivity to the plasma followed by the potassium from the carbonate reacting with sulfur dioxide to form additional potassium sulfate. This reaction is essentially quantitative, so that provision of sufficient potassium carbonate can result in the emission of essentially no sulfur oxides.

Nitrogen Oxides

An MHD combustor operates so much hotter than a usual furnace, $4500^{\circ}F$ versus $2500^{\circ}F$, that copious amounts of NO_x are formed, up to ten times as much as from a PC furnace, despite the initial substoichiometric combustion. Controlled slow cooling of the gas and recirculation of flue gas to hold down the temperature of final combustion results in a reduced final NO_x emission, one which meets the standard.

DISCUSSION

All of the power plants considered have been designed to meet or better the emission rate performance standards for air emissions as shown in Table 2. The fossil fueled power plant will just meet the standards. The low temperature of combustion and NO_x decomposition reactions inherent in PFBC account for its low NO_x emissions. The baghouse used for final particulate cleanup accounts for the low particulate emissions. The combined cycle power plant will satisfy SO_x regulations but should be below those for NO_x and particulate matter. The magnetohydrodynamic power plant will emit essentially no SO_x while the particulate and NO_x emissions will meet standards. The fuel cell power plant will have the lowest emissions of all due to the rigid requirements of the fuel cells and the use of a low temperature catalytic burner.

The above paragraph was based on emission rates. Considering the absolute amounts of regulated pollutants emitted, shown in Table 3, the fossil fueled plant will emit the most, followed by the combined cycle and the pressurized fluidized bed combustion power plants having similar emissions, than by the magnetohydrodynamic plant, with the fuel cell power plant having by far the smallest total amount of pollutant emissions. All these emissions should have added to them the fugitive emissions from the coal pile and coal handling and preparation steps, and the ash handling steps. Considering all the emissions in Table 3, including CO_2, hardly alters the situations.

CONCLUSION

All the subject power plants will have atmospheric environmental intrusions that are currently tolerable. The plants can be ranked, as in Table 4. This ranking is somewhat subjective. It does not take into account any weighting by the effects of one pollutant over another, which perhaps should be done. Under any ranking system, the molten carbonate fuel cell and the magnetohydrodynamic plants can hardly be disloged from their placings and the pulverized coal plant will probably always be lowest ranked.

TABLE 3

EMISSION AMOUNTS FROM COAL CONVERTORS

(LB/HR)

PLANT	PARTICULATE	SO_x	NO_x	CO_2
PC	147	2940	2940	995,000
PFBC	128	2560	850	958,000
CGCC	138	2750	920	931,000
MCFC	~0	~0	~0	640,000
MHD	123	~0	2470	880,000

TABLE 4

COAL CONVERTORS EMISSION RANKING

(BEST TO WORST)

MOLTEN CARBONATE FUEL CELL

MAGNETOHYDRODYNAMIC

PRESSURIZED FLUIDIZED BED COMBUSTOR

COAL GASIFICATION COMBINED CYCLE

PULVERIZED COAL

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FIGURE 1

PULVERIZED COAL PLANT HEAT AND MASS BALANCE

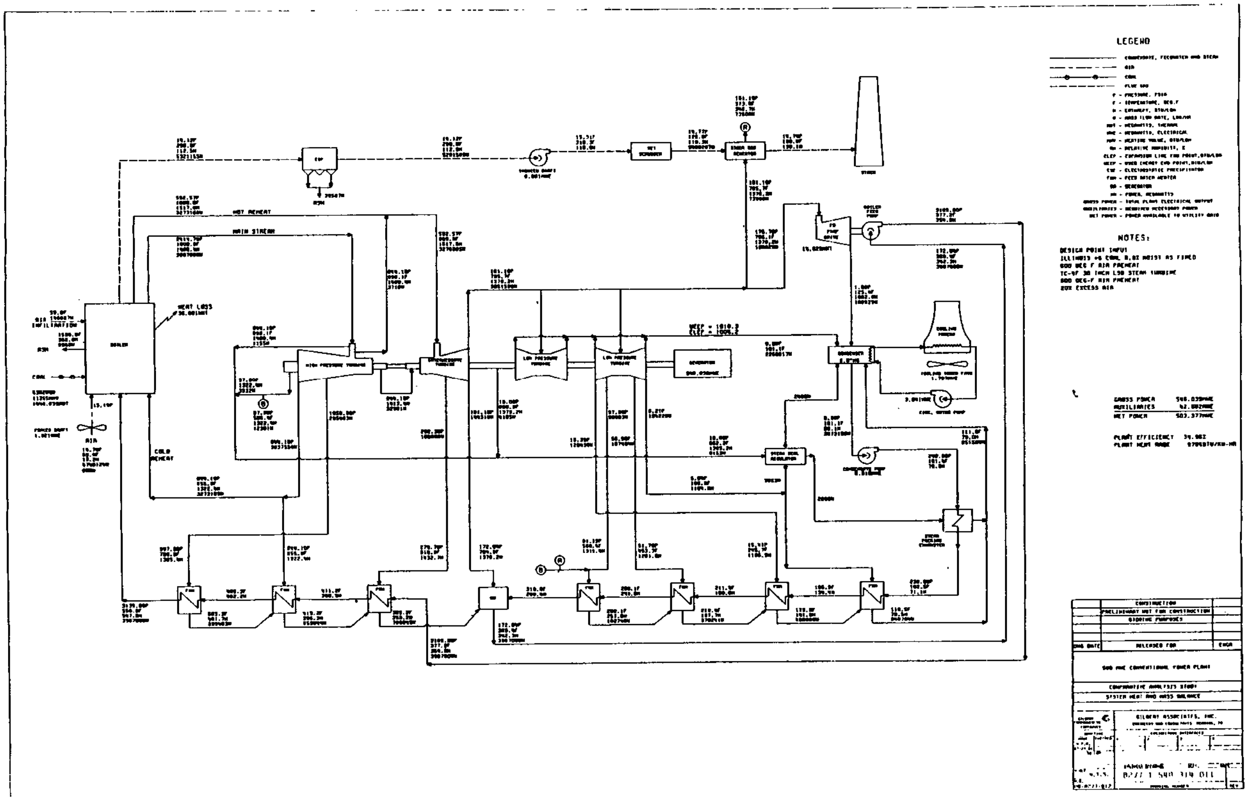

FIGURE 2

PULVERIZED COAL PLANT

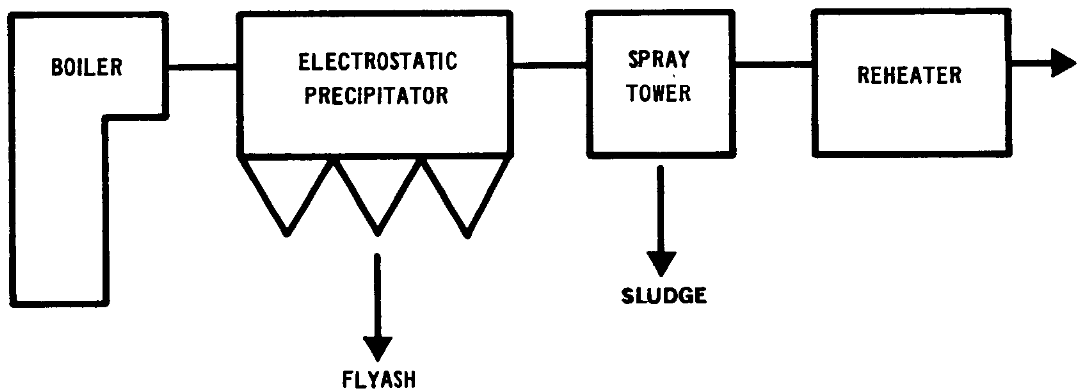

FIGURE 3

PRESSURIZED FLUIDIZED BED PLANT HEAT AND MASS BALANCE

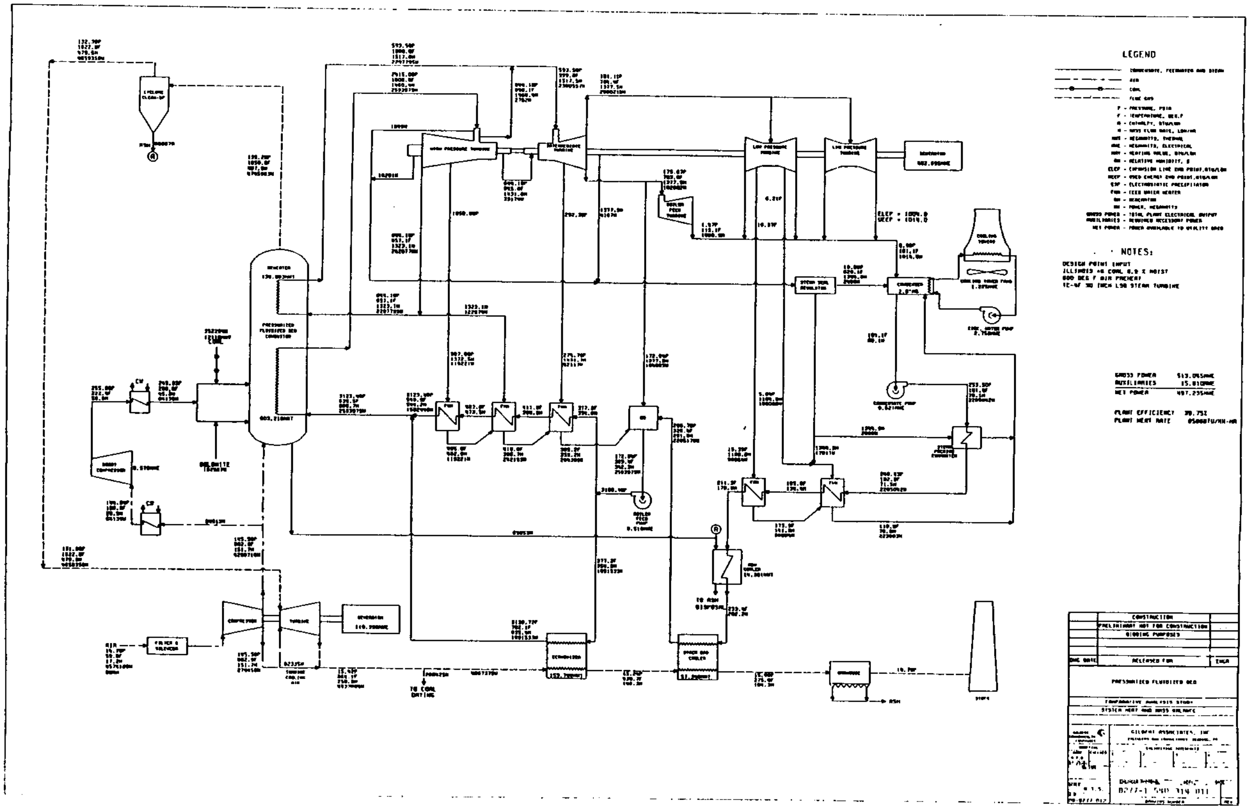

FIGURE 4

PRESSURIZED FLUIDIZED BED PLANT

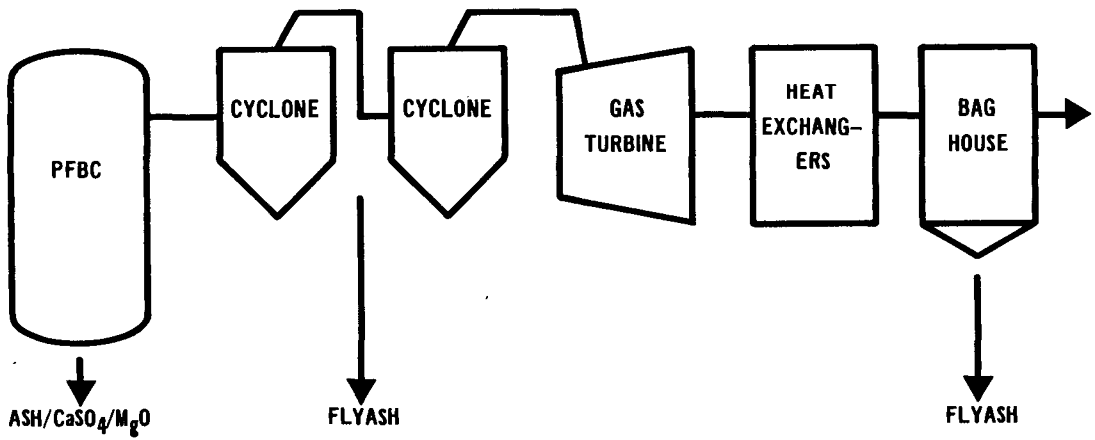

FIGURE 5

GASIFICATION COMBINED CYCLE PLANT HEAT AND MASS BALANCE

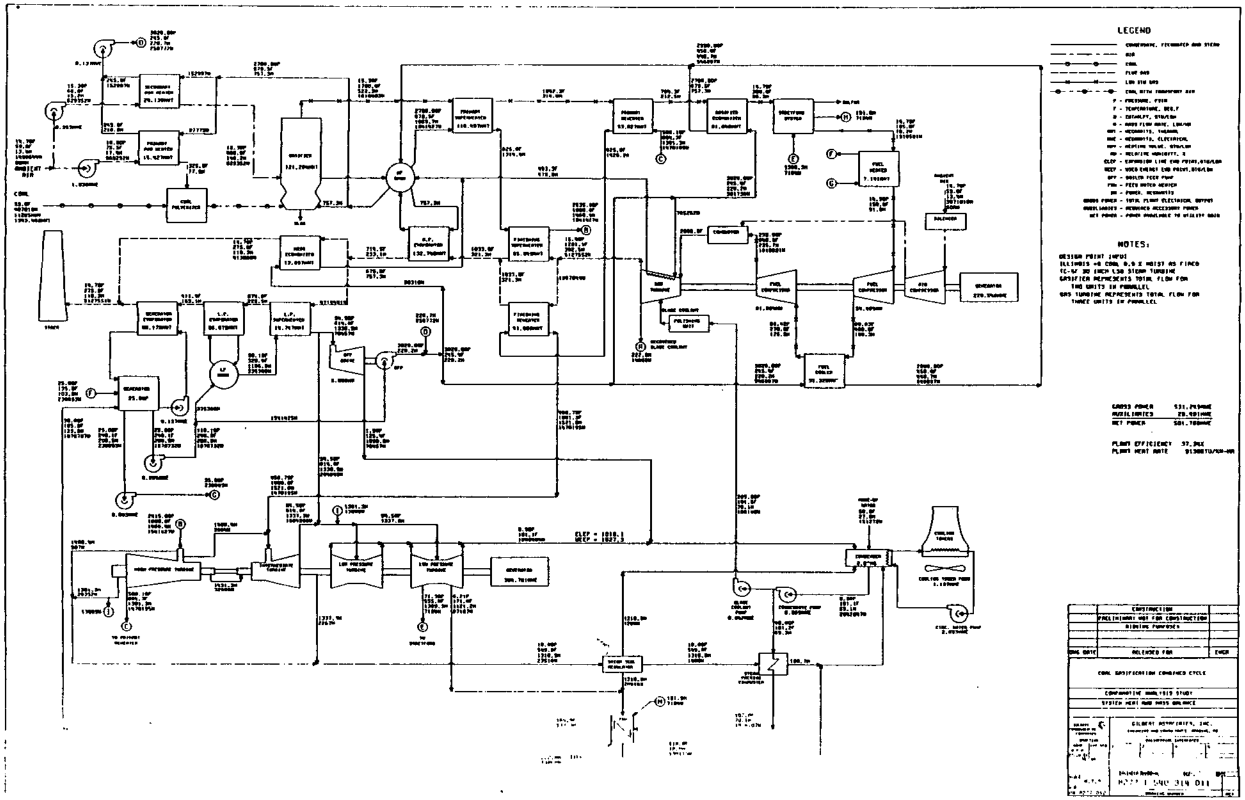

FIGURE 6

COAL GASIFICATION COMBINED CYCLE PLANT

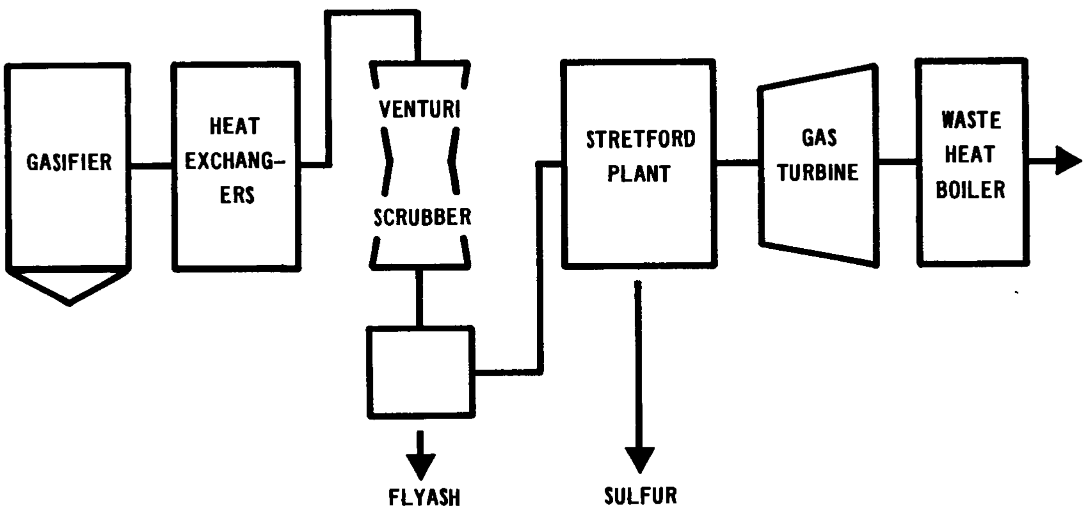

FIGURE 7

FUEL CELL PLANT HEAT AND MASS BALANCE

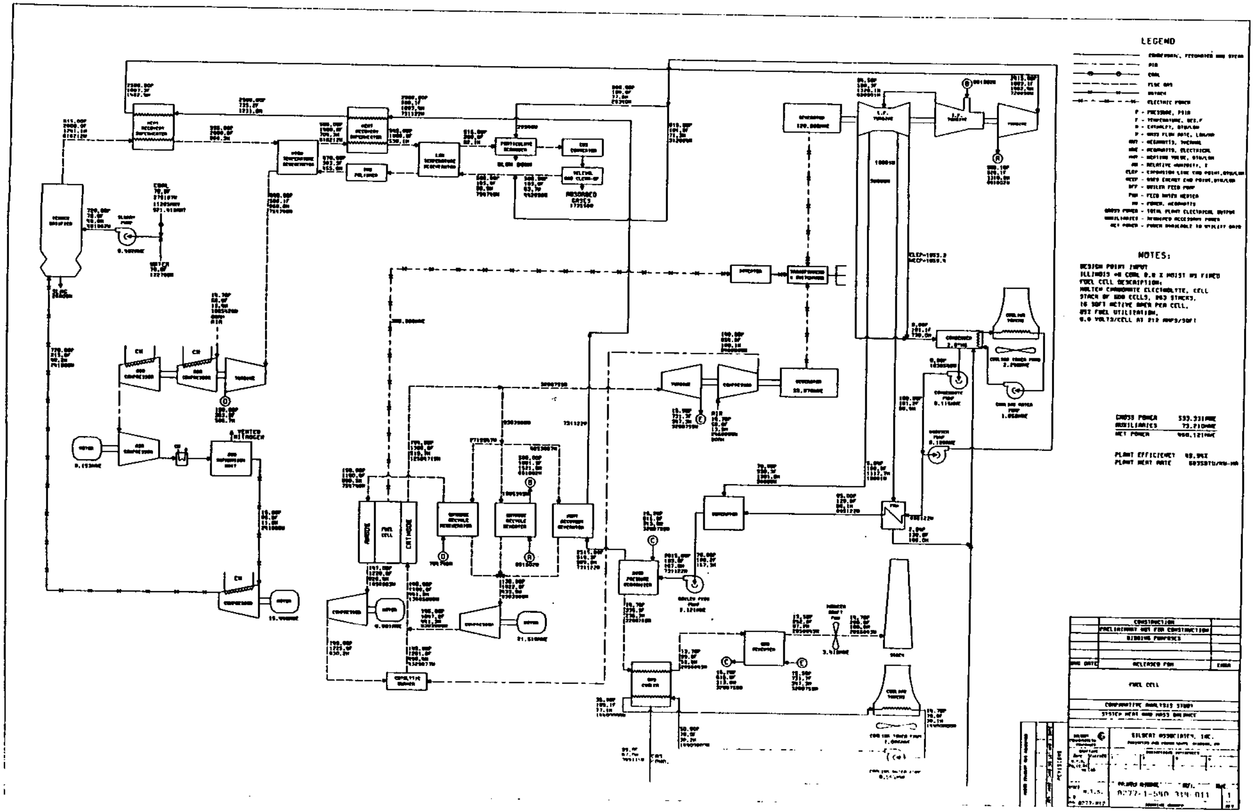

FIGURE 8

MOLTEN CARBONATE FUEL CELL PLANT

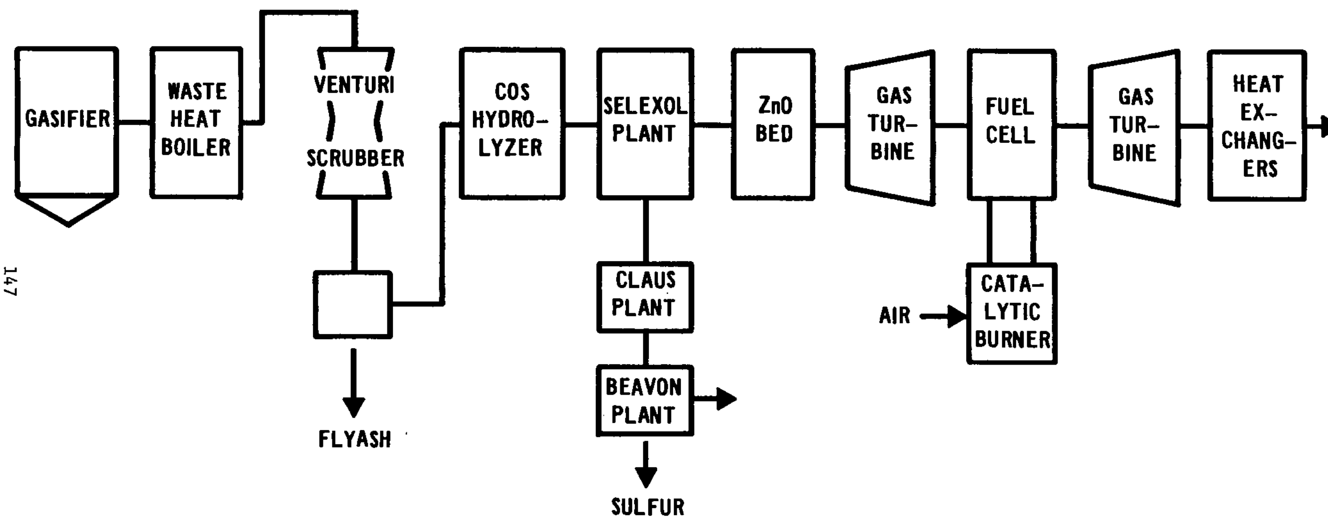

FIGURE 9

MAGNETOHYDRODYNAMIC PLANT HEAT AND MASS BALANCE

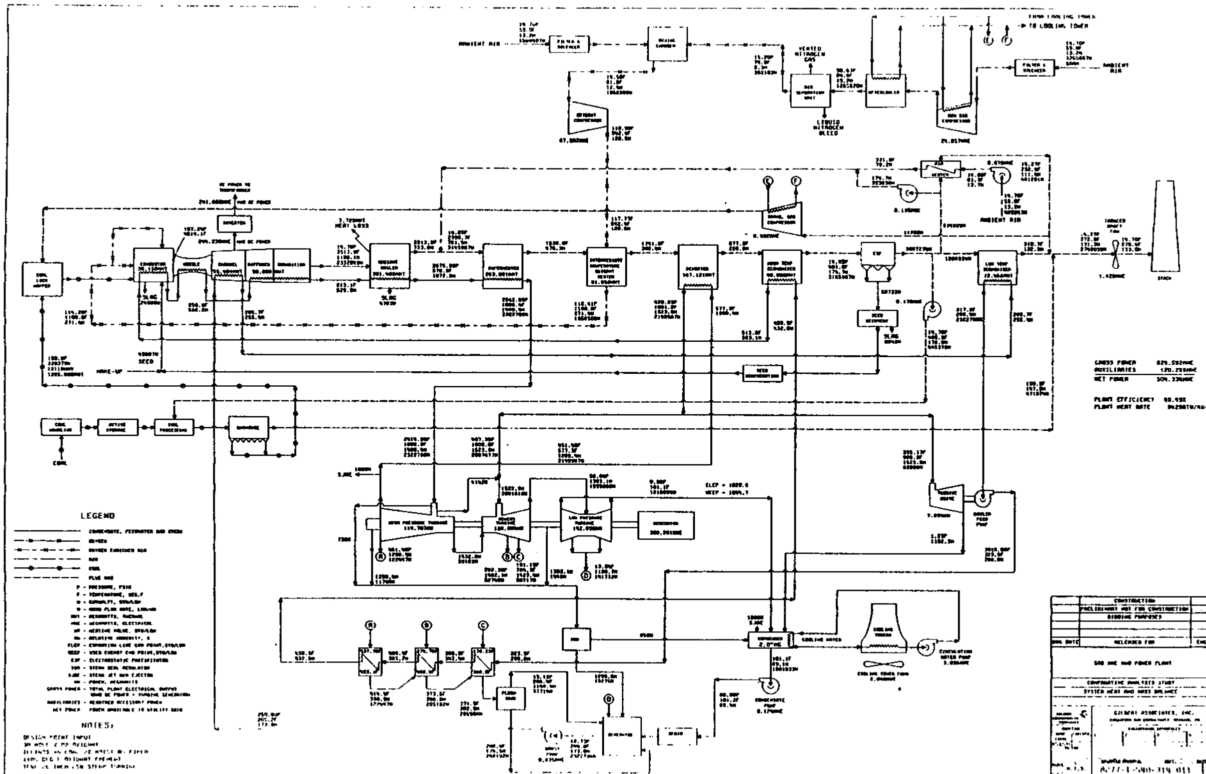

FIGURE 10

MAGNETOHYDRODYNAMIC PLANT